Proceedings Paper:

Gollin, D., Bowman, E. orcid.org/0000-0001-7868-6688 and Shepley, P. (2015) Granular temperature measurements of uniform granular flows. In: Rinaldi, V.A., Zeballos, M.E. and Clariá, J.J., (eds.) Deformation Characteristics of Geomaterials. The 6th International Symposium on Deformation Characteristics of Geomaterials, 15-18 Nov 2015, Buenos Aires, Argentina. IOS Press . ISBN 978-1-61499-600-2

Granular temperature measurements of uniform granular flows

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Abstract. The investigation described here consists of a study aimed at validating a reliable and straightforward method to estimate granular temperature. Experiments on dry granular flows of sand and spherical beads were performed on a simple inclined chute geometry. Flow properties at the sidewall were obtained from images recorded at high frame rate using particle image velocimetry. Direct measurements of granular temperature were estimated by means of statistical analysis. Low values of granular temperature were measured indicating that a collisional state was not fully achieved. Hence, we deemed the flows to fall into the dense flow regime. In spite of this, the dynamics of the flow exhibited a highly inhomogeneous behaviour evidenced by our results, which showed the variable nature of velocity fields and granular temperature observed.

Keywords. Granular flow, granular temperature, particle image velocimetry

1. Introduction

Granular materials are encountered in a diverse range of geophysical contexts such as granular chute flows, landslides and debris avalanches. The majority of these processes undergo rapid rates of deformation in which momentum transfer is mainly carried by frictional and collisional stresses, although shear stresses in the interstitial fluid can represent an additional element of momentum exchange. More specifically, collisions between neighbouring particles will cause random fluctuations in the particle velocity, reminiscent of the thermal fluctuation motion of molecules [1] in kinetic theory. The random components that generate particle stresses through collisions can be related to the concept of granular temperature. This entity represents the basic concept underpinning the kinetic theory of granular gases. Granular temperature provides a measure of the energy associated with the fluctuating nature of the granular motion, i.e., the agitation within the medium. Thus, granular temperature may be used to characterize the flow regime and infer the ability of a granular material to flow.

Generally, granular systems are easier to treat numerically than they are experimentally [2,3]. Kinetic theory and its extensions have been idealised by making strong assumptions about the inelasticity, shape, and rotational motion of the grains [4]. Moreover, the introduction of kinetic theory and similar microstructural theories has created new challenges to experimentalists. Many parameters introduced in the simulations are hard to measure in laboratory tests and direct quantitative comparison

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with experiments is difficult to make. Yet verification of the prediction of models should always be tested and validated to results taken from experimental investigations. As a consequence, it is extremely important to provide experimental data against which theories and simulation can be judged.

Direct estimations of granular temperature are rarely found in the literature and in any case are difficult to interpret. However, the last few decades have seen the development of new optical techniques along with high-speed recording systems, which can now enable the acquisition of robust measurements of particle motion. A variety of instrumentation and mechanical devices are utilized to obtain such measurements. Reynolds et al. [5] analysed the bulk motion of granular mixtures in a high shear granulator. Owing to the experimental configuration, measurements were limited to surface velocity obtained using particle image velocimetry (PIV). The analysis of the temporal velocity was set at a single localized position in the centre of the measured surface velocity. The analysis was then extended to extract velocity correlation and granular temperature at a length scale of a single particle. Inclined chute geometries have also been used. Azanza et al. [6] measured granular temperature in dry, highly energetic and diluted flows. A two-dimensional analysis was performed by constraining a single layer of particles in a narrow channel. Armanini et al. [7,8] studied saturated granular flows in a recirculating flume. In their investigations, flows were observed at the near wall and, to some extent, at a certain distance from the sidewall [8]. Granular temperature profiles were also extracted for different flow regimes by using Voronoï imaging. Hanes and Walton [9] carried out numerical simulations in order to interpret flow properties interior to the flow down a bumpy incline and compared these with experimental results taken at the sidewall. Interestingly, they noted a discrepancy in the variation of granular temperature in comparison to the sidewall. They deemed the boundary conditions responsible for strong three-dimensional structure in the flow, strongly influencing the measured granular temperature.

Physical modelling is usually constrained by the impracticality of obtaining measurements of the internal character of the flow. Indeed, measurements of velocity fields in both dilute and dense granular systems are often limited by the opaque nature of such flows. For this reason, flowing materials are probed at the boundaries where the conditions control the flow properties. Alternative non-intrusive techniques can then be used to overcome these limitations. In the context of geophysical flows, Sanvitale and Bowman [10] performed physical experiments on an unsteady non-uniform saturated granular medium. Their technique (see [11]) allowed for the acquisition of flow properties internally to the bulk granular mass. They used the same approach as [5] to estimate granular temperature. The results were encouraging even for an agitated flow composed of different particle sizes. However, further validations and supporting evidence are required to examine the validity of this technique to correctly capture granular temperature.

In this paper we attempt to measure granular temperature for flows of dry nearly monodisperse sand and spherical ceramic beads. Our approach to estimate flow fields is similar to previous works by Reynolds et al. [5] and Sanvitale and Bowman [10]. They have suggested that a combination high-speed high resolution image acquisition with PIV provides a possible solution to determine granular temperature. We present our results for two flows down a flat, frictional incline and discuss the significance of the granular temperature profiles we have extracted.

2. Physical experiments

2.1. The apparatus

A small inclined chute has been developed in order to reproduce dry granular flows. The flume is a sloping rectangular 10 cm wide and 150 cm long channel that can tilt from horizontal up to 45°. The choice of such a narrow channel was made to constrain the flows between well-defined boundaries, thus allowing measurements to be taken at the sidewall. At one end, the material is held inside a hopper, which can contain approximately 10 kg of material. A double-gate opening system is used. Before releasing the material, the first gate is set at a certain height from the flume bottom, which in turn reflects the thickness of the granular flowing layer. The thickness is well controlled by the gate, although it is unlikely to be equal to the opening. Interchangeable sheets, onto which different particle sizes can be glued to control basal roughness, cover the bottom of the chute. The walls are made of transparent material; therefore observation may be obtained throughout the entire length of the chute.

2.2. Data acquisition analysis

The optical equipment consists of a Phantom Miro 310 high-speed camera, which is supplemented with two light sources. Images were captured at a frame rate of 10,000 frames per second. Camera resolution used was 448 x 448, which roughly corresponds to an image size of 32 x 32 mm (Fig. 1)

A particle image velocimetry (PIV) algorithm [12] was employed directly to the captured images and was found sufficient to determine the velocity fields. The software allows a static mesh to be kept in the same location while the granular mass is flowing. This PIV is designed for non-transparent material and does not require any tracer particles. The surface structure of the flow is sufficient to determine the vector field via the cross-correlation analysis between interrogation regions in the first and second images. Different square interrogation sizes were used, specifically 16, 24, 32, 40 and 48 pixels [10,12]. The corresponding spatial regions are approximately 1.15, 1.7, 2.5, 2.8 and 3.4 mm. The size of the interrogation area has an important effect on the range of velocity fields that can be determined [5]. Notably, patch sizes smaller than the particle diameter does not produce sufficient textural information. Conversely, larger interrogation area implies that the measure will refer to an ensemble of particles.

2.3. Experimental procedure

Granular materials used in this study are sand and spherical ceramic beads. Two granular flows are presented here. For clarity we will refer to SaT1 for the flow of sand and BeT2 for the flow of beads. Beads were selected because of their spherical shape which are typically assumed in the majority of the granular flow theories. For the flow of beads the flume bottom roughness was made by gluing the same spherical material. In case of sand, after some trials the roughness was substituted with a finer sand fraction in order to allow analyses at less steep inclinations. SaT1 consists of a batch of sand that was sieved to produce a nearly monodisperse material with particle sizes between 1.4 and 1.7 mm. In comparison, ceramic beads are nominally 1.4 – 1.6 mm in diameter. The static friction angles, determined from a tilt test, were 34.5º for sand and

24º for beads, and dry bulk densities of 1.52 g/cm^3 (loose density) and 2.43 g/cm^3, respectively.

SaT1 was released from the hopper at an inclination of 38º. The flume was tilted at 32º for BeT2. The camera was positioned 30 cm before the outlet where the flowing material is more likely to reach an approximately steady regime. The analysis performed here is valid if the flows are uniform in the direction parallel to the main plain of sliding. The uniformity was checked by visual inspection. We selected temporal regions where flow exhibited no detectable variations in the depth profile. The nominal flow depth was 20 particle diameters for SaT1 and 18 for BeT2. Videos were recorded at the initial frame rate of 10,000 fps over 0.5 s, producing 5,000 frames. At a later stage, we reduced the temporal resolution to 5,000 fps and 2,000 fps by removing images from the original recording. In doing so, we kept the same flow dynamics but established different frame rates at which the flow could be probed.

Granular temperature requires the determination of kinematic properties, e.g. fluctuation velocity. Reynolds et al. [5] showed that granular temperature might be measured by statistical analysis. If the fluctuations are assumed to be normally distributed, granular temperature is given by the variance of the fluctuation velocity. Similarly, the standard deviation of velocity can be used as a good indicator of the intensity of vibrational kinetic energy in flowing material [9]. If the mean velocity of all particles is constant, the variance of the velocity may characterise the particle granular temperature. Sanvitale and Bowman [10] adopted this approach; the same analysis is also followed in this study.

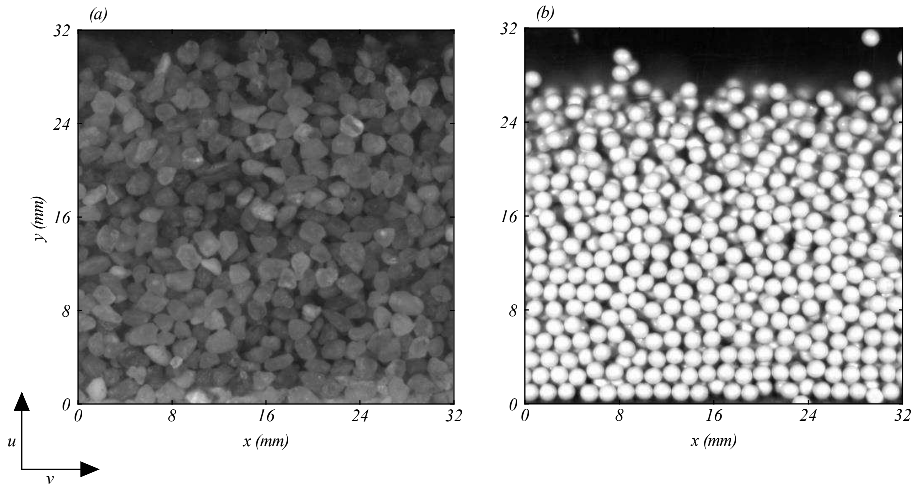

Figure 1. Example of images extracted from sand (SaT1 – (a)) and beads (BeT2 – (b)) flows.

3. Results and analysis

We used particle image velocimetry (PIV) to measure the velocity fields in our flows. A careful judgement with regard to the interrogation size for the cross-correlation analysis has to be made in order to estimate the correct flow properties. Notably, a patch size of the order of the particles generates the most accurate values of granular temperature [5]. Larger interrogation regions cause a reduction in the measured fluctuation velocity that in turn reflects a reduction in measured granular temperature. As we employed material uniform in diameter, two fixed interrogation areas were considered. 32 x 32 and 24 x 24 pixels patches were chosen to analyse SaT1 and BeT2, respectively. Note that a 24 pixel patch corresponds to 1.7 mm, hence it covers the entire surface of a singular bead. A slightly larger size was required for SaT1 to take into account the diverse shape of the particles. All the results reported here are shown for these two interrogation sizes only. We evaluated the influence of patch size and found what was previously stated in [10]. That is, very small interrogation areas produce high levels of noise whereas larger areas progressively reduce the value of fluctuation velocity and hence, granular temperature.

Velocity components for the two flows are shown in Fig. 2 (u and v coordinates refer to the perpendicular and parallel flow directions, respectively). It can be seen that a static layer toward the bottom of the flow characterizes SaT1 (Fig. 2(a)). In comparison, BeT2 (Fig. 2(b)) presents an increasing linear velocity gradient from base to the top; in this flow the static layer was absent. Flow properties depend on the shape anisotropy of the material and the velocity profile is strongly controlled by the angularity of the particles [13]. Thus, it is normal to expect that these granular flows show different avalanching behaviour. Velocity fluctuations are shown as the standard deviation of the velocity near the sidewall over the entire duration of the flow (0.5 s). The fluctuations clearly increase toward the free surface, and decrease toward the base. A less clear trend developed for BeT2 (Fig. 2(b)), which may reflect the more collisional behaviour of this material. Nonetheless, the bumpier base may create a slip zone induced by the particles interacting with the base.

In many studies a uniform stationary flow state is assumed for the simplicity it provides in the calculations. However, granular flows always present some degree of unsteadiness. Through our imaging measurements and physical interpretation we assumed that the flow was steady over time, although this is a weak assumption. If plotted in the same figure, velocities calculated between pair of images fluctuate with a clear degree of correlation within a range that has the order of the velocity fluctuations depicted in Fig. 2. Thus, velocities averaged over shorter periods may deviate considerably from the long-term average, suggestive of a mean velocity (relative to local fluctuations) that is essentially unsteady. Many theoretical considerations of

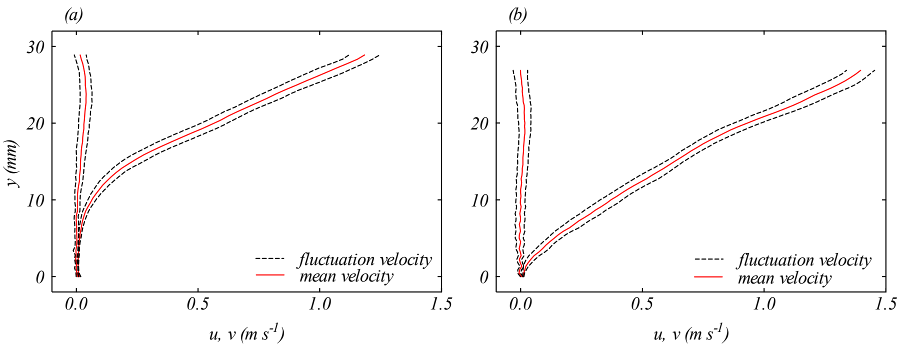

Figure 2. SaT1 (a) and BeT2 (b). Mean and fluctuation velocity profiles.

granular flows derive from fluid mechanical approaches. Careful considerations should be made as to whether the measured temperature derives from real (i.e. random and uncorrelated) fluctuations as defined by the kinetic theory or just "turbulences" generated by the mechanics of the flow. We did not find any suitable explanation; a further investigation is required to ascertain the nature of the fluctuating motion.

This consideration aside, granular temperature was extracted as the variance of the velocities for the entire duration of the flow (0.5 s); temperature was then taken as the non-stationary component of the local mean velocity. The fluctuation velocity gradient perpendicular to the flow direction (u) showed non-negligible effects. Thus, in the calculation we have taken both u and v components into account.

Granular temperature profiles are shown in Fig. 3. The most striking result regards the magnitude of granular temperature. Our values ranged from 0.0 up to approximately 0.005, which are not in agreement with measurements for collisional state motion found in the literature. Drake [14] reported granular temperature between 0.2 and 0.4 for very disperse and diluted dry flows. Lower values, varying around 0.1, were found in much denser flows. From numerical simulation down a bumpy incline, Hanes and Walton [9] estimated temperature at the sidewall up to 0.01. In saturated granular flows for material sliding over a dense layer of particles Armanini et al. [7] measured granular temperature of 0.05 at the surface while decaying to 0.0 at the bottom. It seems that our flows did not reach a fully collisional state, falling into the dense flow regime [15]. In this regime particles remain closely packed and interact by enduring contacts and few inter-particle collisions. A contact network and unevenly distributed structures evolve throughout the flow. The length scale of the correlated motion (i.e. the degree to which particles act as a cluster rather than individually) has an impact on the measured granular temperature: internal momentum transport is carried by the coherent motion of correlated particles with a low level of stress generation; collisions are less frequent which in turn reduces the calculated granular temperature. Nevertheless, the boundary condition at the sidewall may also act to damp the generation of fluctuating motion [16]. Additionally, uncertainties might also be connected with the PIV algorithm we used to estimate granular temperature. Granular temperature profiles in Fig. 3 do not show a linearly increasing gradient, but different "peaks" appear. The "peaks" in curves shown in Fig. 3 are representative of the highly variable nature of the flow. Similar profiles taken on the top of flows from numerical

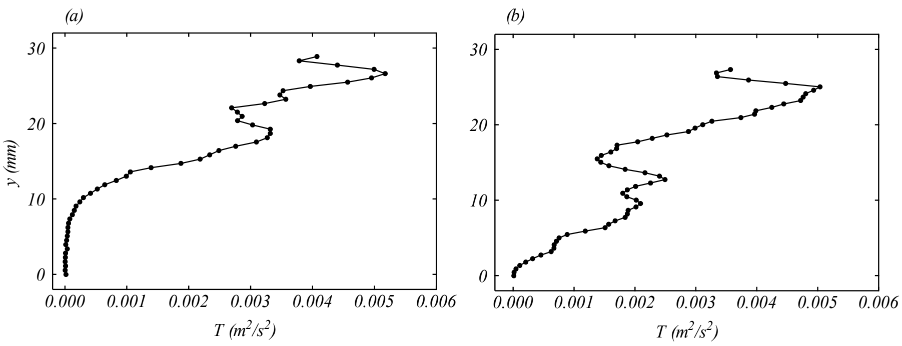

Figure 3. SaT1 (a) and BeT2 (b). Granular temperature profiles.

simulation and through the sidewall of saturated granular flow in experimental work have been previously observed [9,10]. While it is possible that fluctuation velocity and therefore, granular temperature, averaged over longer a period of time may produce smoother curves, interestingly, a system transition forms in the middle of the flow in both tests. Granular temperature drops at around 20 mm for SaT1 and 15 mm for BeT2. Subsequently, the gradient returns to be sloped in the flow direction. This may be indicative of a change of stress transfer mechanism to one which is more frictional. The discrepancy towards the free surface may be linked to the loss of textural information in PIV when the flow becomes more diluted.

Gopalan and Shaffer [17] argued that many experimental techniques are unable to accurately measure the random components of velocity. Before decomposing the velocity field into its mean and random quantities, the necessary sample rate for full temporal resolution variations should be established. Our results are based on images captured at 10,000 fps. The same profiles plotted for 5,000 fps only shows slight reductions of granular temperature. In contrast, at 2,000 fps the system transition disappears indicating a loss of recorded fluctuations and consequently of granular temperature, hence it would appear that 5,000 fps is the limit here.

4. Conclusions and Future work

Granular temperature is a variable upon which constitutive behaviour of granular material can depend. Thus, direct measurements of this entity are very useful to elucidate the extremely variable nature of granular flows. A simple inclined chute geometry has been used to produce granular flows in a laboratory-scale environment. We have extracted granular temperature from two different flows by means of statistical analysis and PIV. The analysis was carried out at high temporal resolution due to the unsteady nature of the motion and showed that while velocity measurements taken over a long time-scale may suggest steady flow, over a shorter period, significant correlated velocity fluctuations may also occur which could be due to granular turbulence rather than granular temperature via collisions, as usually understood.

Despite the few studies mentioned in this paper, the authors do not know of any other study that gives a direct measure of granular temperature for flows down inclines by means of PIV. Hence, we need to ascertain the reliability of our method. It would be interesting to compare measurements provided by PIV against alternative techniques such as particle tracking (PTV). Moreover, additional work has to be conducted to verify the influence of the interrogation region and temporal resolution.

Our results are in disagreement with values of granular temperature for collisional state motions found in the literature. It appears that our flows fall into the dense flow regime. While has been suggested that kinetic theory may also be valid for relatively dense flow [18,19] a more careful judgment on the laboratory conditions has to be made. Perhaps, creating a more collisional flow can provide further insights on the validity of this method and how far it can be pushed.

We have proposed a method that might provide a means to estimate the true granular temperature and which may prove particularly useful for well-graded (polydisperse) systems [10]. The mechanics presented here are strongly influenced by the material characteristics of the flow particles, friction and additional effects induced by the boundary conditions. We are aware of the implications induced by the sidewall and the material we have chosen. However, this is a preliminary study devoted to better understanding how far this approach could provide valid and explicit results. Our final goal is to verify the applicability of this method into three-dimensional cross-sections to elucidate the highly inhomogeneous rheological behaviour of natural granular flows.

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